Spectroscopic analysis in hard x-rays and gamma rays

David Smith, UCSC
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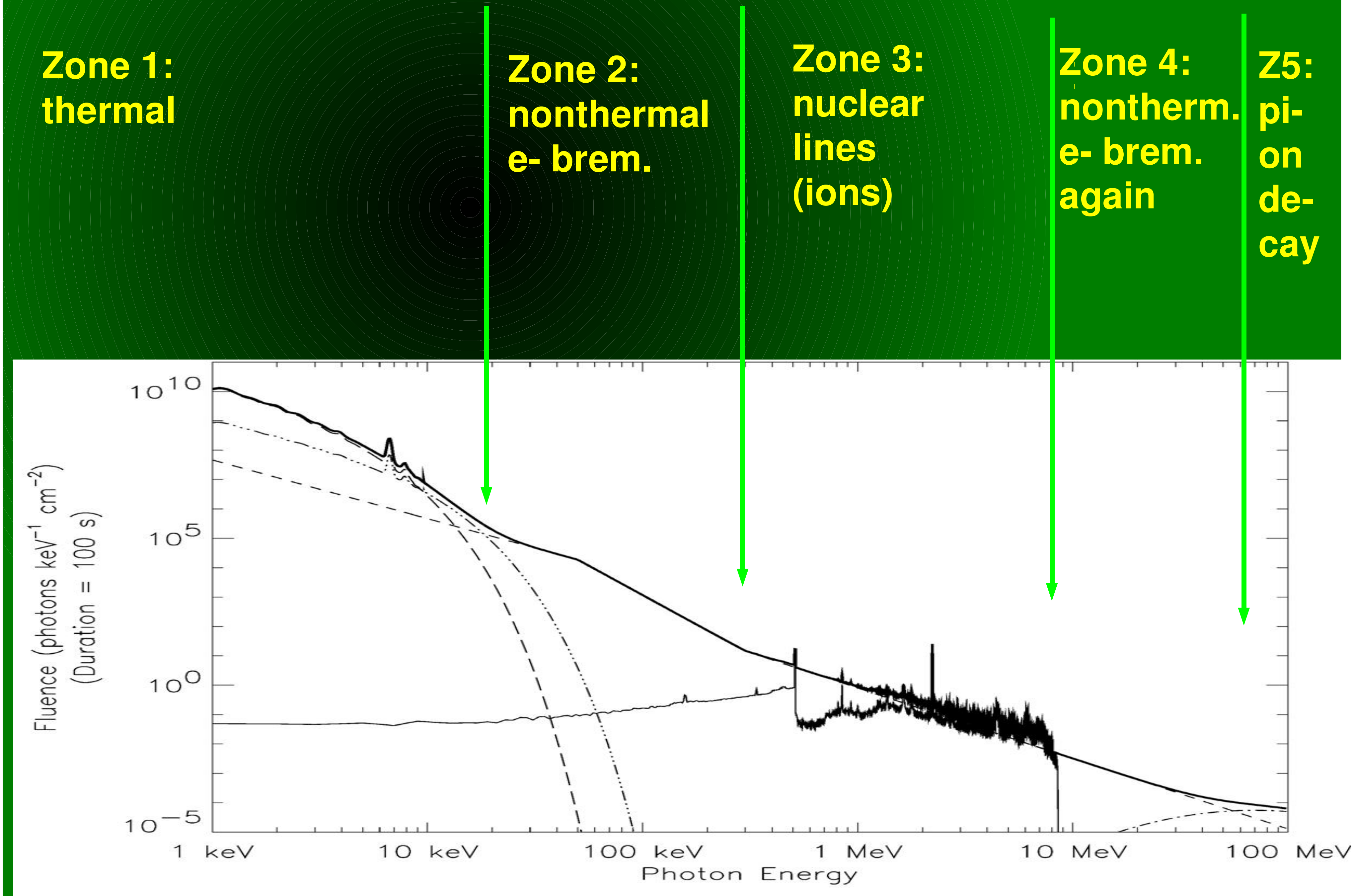
We collect and count individual photons



Reminder of why we want to do solar spectroscopy:

Temperature and density plasma diagonstics in thermal x-rays

Inversion of hard x-ray spectrum to accelerated electron spectrum

Gamma-ray line ratios for accelerated ion spectrum & composition

Nuclear de-excitation line shapes for ion angular distributions & composition

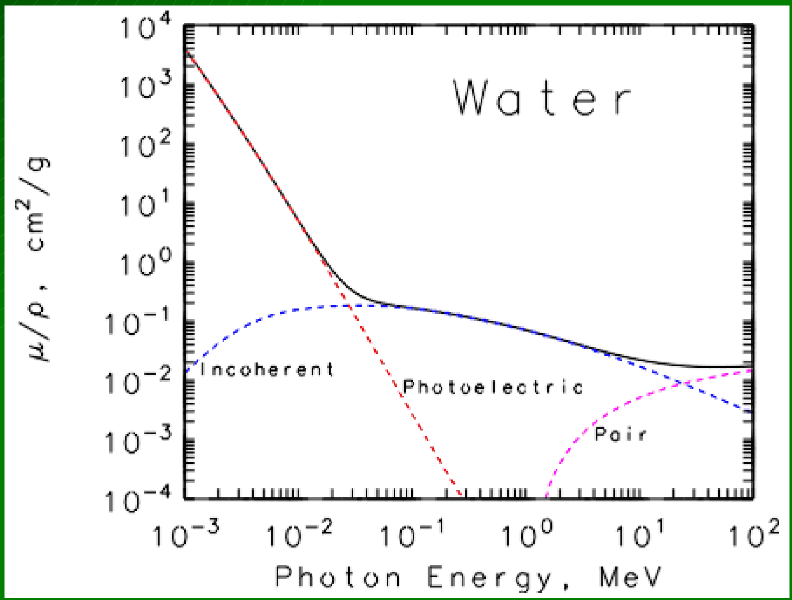
Positron-annihilation line shape for flaring atmosphere temperature and density

Pion decay spectral signature for highest energy ion flux

[See slides of talk by R. Murphy]

Detectors and interaction physics vs. energy:

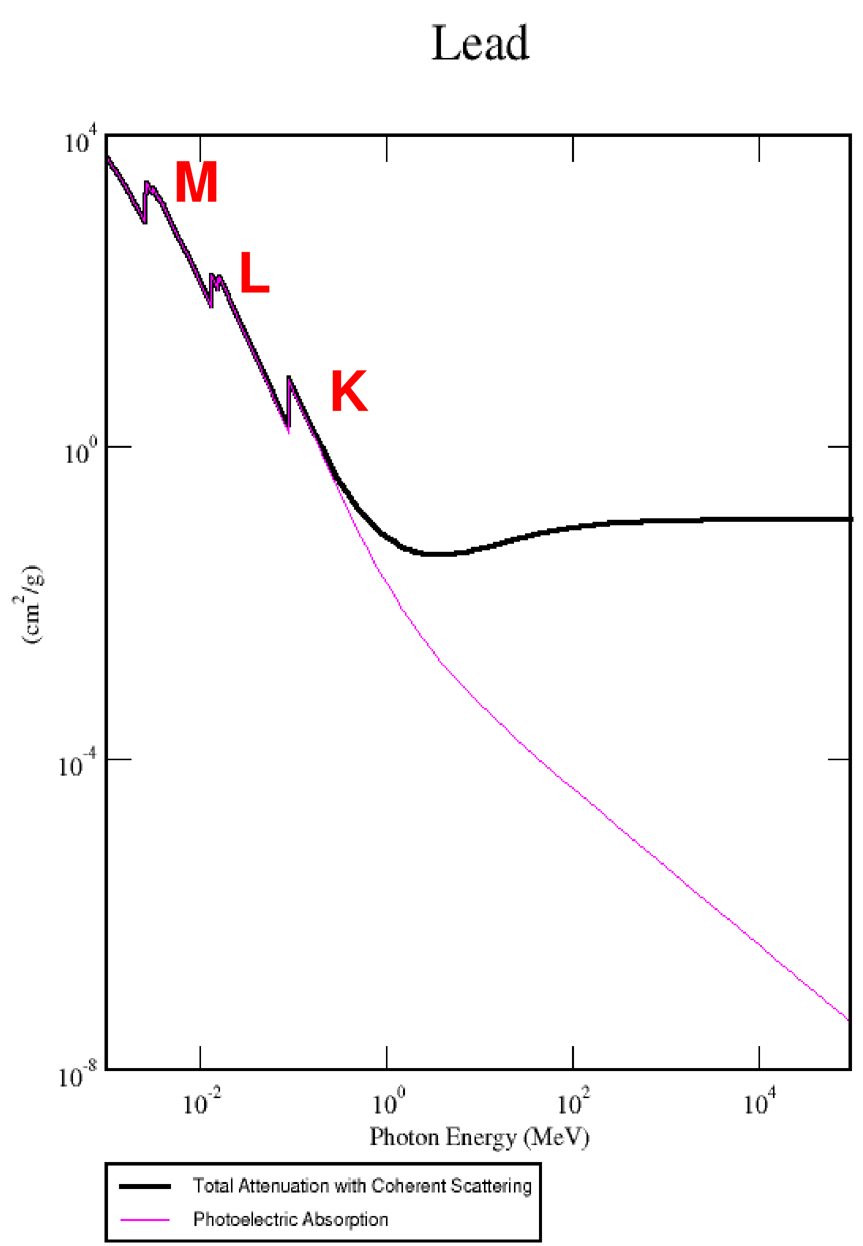
Zone:	Detectors:	MeV:	Physics/energy losses:
	CCDs	0.003	Photoelectric absorption
1	Thicker Si, gas prop. ctrs	0.01	k-shell escape
	CdTe, CZT	0.03	
2	Germanium detectors	0.1	
		0.3	Compton scattering
3	Scintillators: NaI	1	Compton escape
	CsI	3	Pair production
4	BGO	10	511 photon escape
		30	electron escape
5	Pair tracking	100	
	(Gas or silicon again,	300	
	scintillation fibers)		



Photoelectric absorption:

Dominates below about:
50 keV in Si
150 keV in Ge
500 keV in Pb, BGO

Material becomes more transparent just below "edge"; possibility for k-shell photon escape.



Compton scattering:

Compton-dominated regime has minimum cross-section; escape is common. RHESSI detectors are only about 15% photopeak efficient at 2.2 MeV (solar neutron capture line)

Free-electron approximation good but not perfect (opacity related to electron density only)

Energy lost to Compton electron is a function only of scatter angle and starting energy (conservation of energy, momentum):

$$\frac{1}{E_{scatter}} = \frac{1}{E_{incident}} + \frac{1-\cos\theta}{511}$$

Cross-section is more complicated; there are forward and reverse peaks at semirelativistic to relativistic energies

Scatter prefers to preserve direction of electric field vector when scattering near 90 degrees -- therefore azimuthal angle distribution is a good polarization diagnostic until 90-degree scatter becomes rare at high energies.

Compton scattering can take place

- at the Sun
- off the spacecraft into the detector
- off the Earth's atmosphere into the detector
  - (if the Earth is nearby)
- out of the detector

For example

Forward (small-angle) Compton scattering of the 2.2 MeV neutron capture line from deep in the solar atmosphere produces a "step" continuum just below the line (T. Vestrand et al. 1990, ICRC).

But so does forward scattering in any passive material in front of your detector

Pair Production:

Occurs because the field of the nucleus looks like another photon to a passing energetic photon

Like photoelectric effect, cross sections increase dramatically with Z (strength of nuclear field)

Minimum photon energy is 2*electron rest mass = 1022 keV

But cross section does not become significant until > 2 MeV

Remaining energy goes into kinetic energy of e+ and e-

e+ and e- tend to be forward-beamed, particularly at the highest energies

Positrons must slow down before annihilating (just like in the Sun)

Electron propagation in detector:

Photoelectron, Compton electron or pair ionize detector material and lose their energy

Range is deterministic, not probabilistic as with photons (many interactions). Example: ~1mm at 1 MeV in Ge

The resulting ionization causes the signal in detectors:

Diode detectors (Si, Ge, CdTe): electron/hole clouds are swept to opposite electrodes by applied high voltage and the resulting current is amplified

Scintillators (plastic, NaI, CsI, BGO, etc.): electrons wander the crystal until they relax to the ground state (usually via a dopant site) emitting optical/UV light in the transparent crystal. Light is converted to a current by a phototube, channel plate, semiconductor, etc. and amplified

Best reference for detector interaction physics, detector types and capabilities:

Radiation Detection and Measurement
by Glenn F. Knoll

Advantages of detectors from 100 keV to 10 MeV: Scintillators

NaI: Inexpensive, medium stopping power, moderate energy resolution (about 7% FWHM at 1 MeV), hygroscopic.

CsI: Slightly more expensive, slightly higher stopping power, slightly worse resolution, neutron identification, somewhat hygroscopic.

BGO (bismuth germanate): More expensive, best stopping power per unit mass, worse resolution (about 20% FWHM at 1 MeV). Chosen for shielding or very-high-energy detection. Easily machined, non-hygroscopic

Advantages of detectors from 100 keV to 10 MeV: Ge:
Most expensive, requires cryogenic operation, superb energy resolution (about 0.3% FWHM at 1 MeV), worse stopping power above 500 keV

Detector must operate < 100K so that electron/hole pairs aren't thermally excited.

Purest material existing; low impurities allow lower "depletion" field. Electrical contacts can be traditional diode (n-type, p-type implant) or simply conductive.

Thermal/vacuum enclosure (cryostat) requires space, cost, design effort:

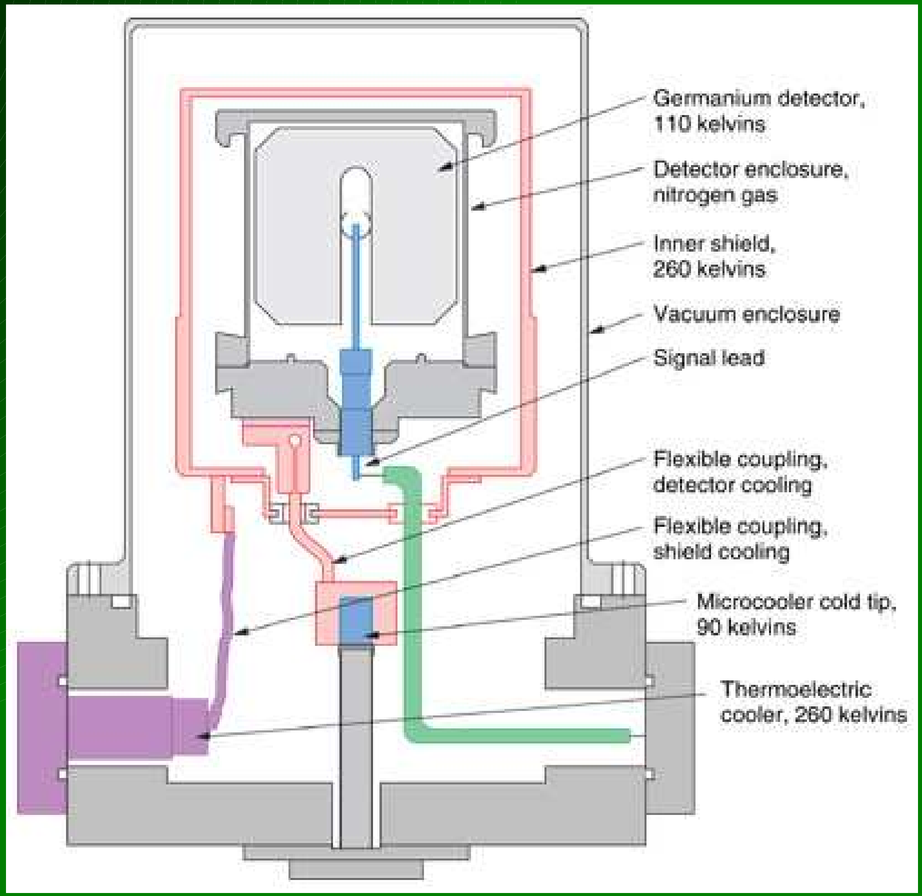


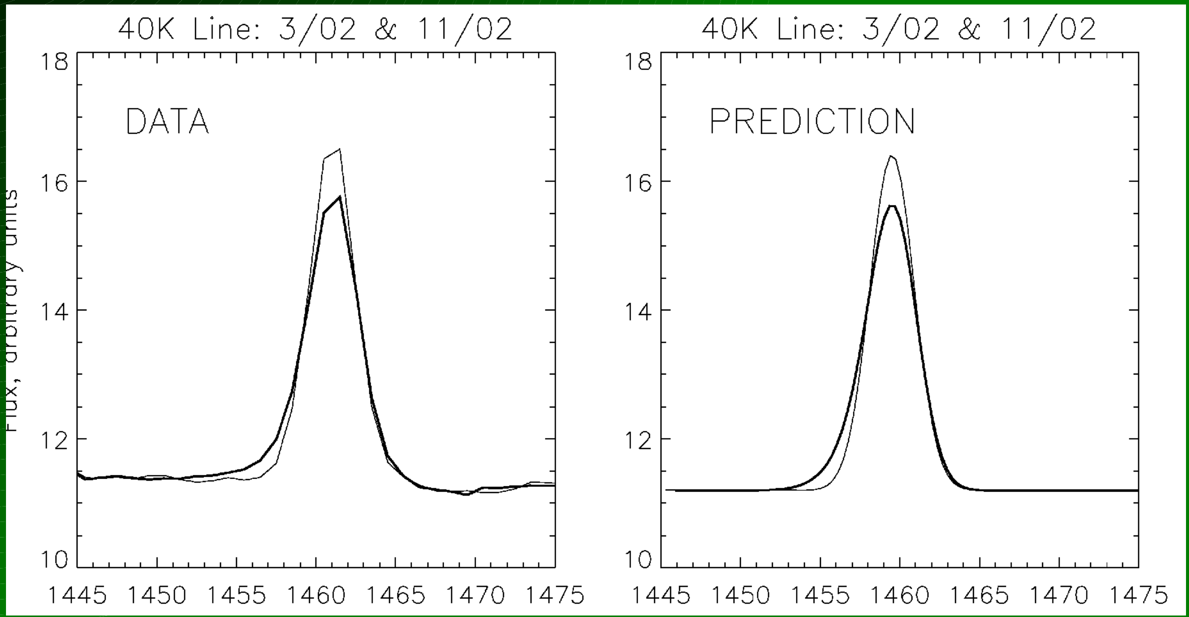
Image: LLNL

Radiation damage in GeDs:

Nuclear interactions of protons/neutrons/nuclei with germanium atoms create lattice defects

Lattice defects trap holes drifting through crystal, so charge is not completely collected; result is a "tail" on the line:

Annealing at ~100C results in removal of this effect; no one knows why.



Culprit particles are cosmic rays (gradual), radiation-belt protons, SEP protons (most sudden, can be most intense)

Other semiconductor detectors (room temperature):

Cadmium telluride/ Cadmium zinc telluride (CZT):

- Small crystals only (about 1cm3)
- Higher "Z" than Ge, better stopping power
- Worse resolution than Ge, better than scintillators
- Very good for hard-x-ray-only work

Silicon:

- large wafers available, but thin (<= 1mm)
- Medium resolution like CZT
- Best for low energies (< 30 keV) or as a pair tracker at high energies (> 30 MeV)

All semiconductor detectors can be read out in strips or pixels for spatial resolution, division of count rates. More demanding on electronics.

Tasks of detector electronics:

Peak identification (triggering)
Amplification and shaping of pulse
Energy measurement (analog-to-digital conversion)
(Anti-) coincidence tagging and handling
Time tagging
Data storage

Usual components, in order:

Preamplifier
Shaping amplifier
Peak detect
A2D
Computer

Removing the effects of the instrument ("data reduction"):

- Channel-to-energy conversion (gain)
- Deadtime correction
- Pulse pileup (highest rates)
- Background subtraction
- Imperfect energy resolution
  - detector physics & electronics
- Incomplete energy collection
  - ("response matrix")

Channel-to-energy conversion:

Detector physics: either completely linear (semiconductor diode) or modestly nonlinear in a predictable way (scintillator light)

Electronics:
- Temperature drifts
- "integral nonlinearity" -- nonlinearity across the scale
- "differential nonlinearity" -- varying widths of nearby channels

This is usually the most straightforward part of data reduction but you have to ask:

- Are there spectral lines you can use to calibrate?
- Will you accumulate enough counts in the time that gain might drift?
- Do you need to include a calibration source onboard?
- What precision do you need to do your science?

Deadtime (livetime) correction:

All detectors take a finite time to process an event; significant issue for flares, where fluxes can be extremely high

- **Intrinsic:**
  - Semiconductor detectors: electron/hole drift times on order of 10 to 1000 ns.
  - Scintillators:
    - Decay time of scintillation response -- NaI, 250ns, others more or less
- **Electronic:**
  - Best spectral resolution requires shaping of pulse to a width of a few microseconds

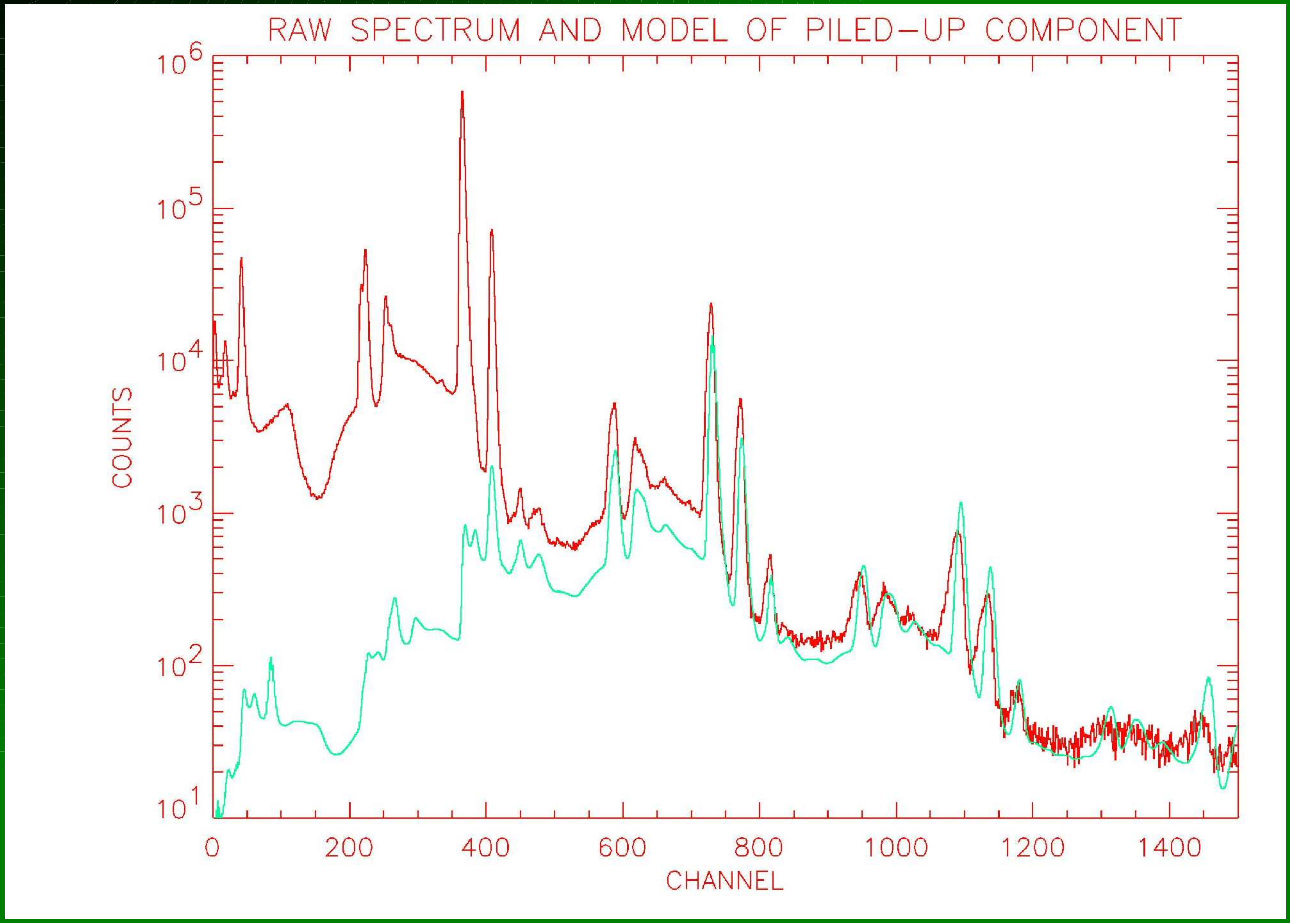
Maximum throughputs vary from a few thousand to a few hundred thousand c/s per detector; one solution is to use many small detectors.

Correcting from detected to corrected count rate fairly easy

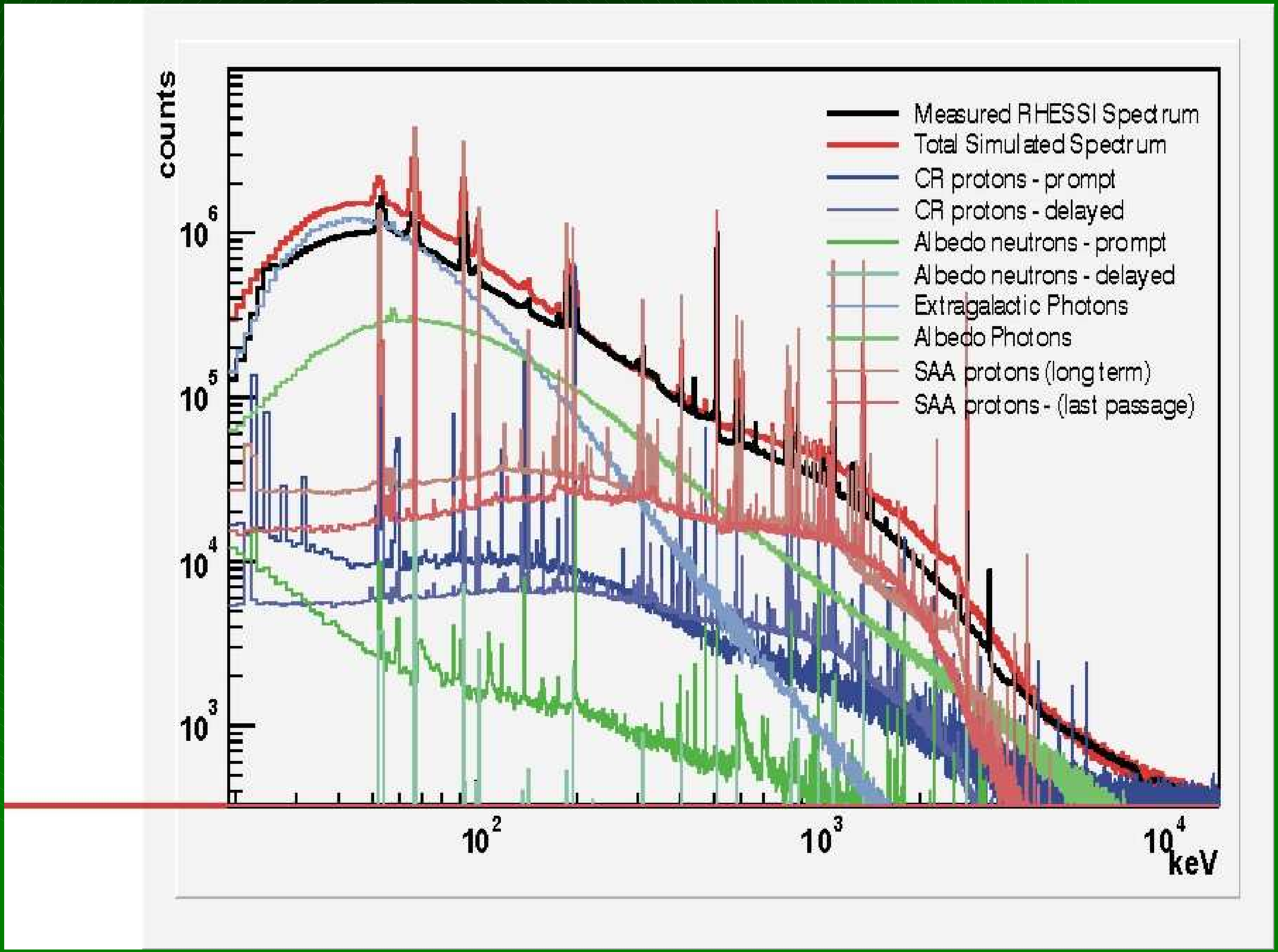
Pileup:
Two pulses close enough together get treated as one by electronics **OR** one pulse has its energy changed slightly by riding on the tail of another. Unavoidable at some level.

"Fast" electronics channel, without high energy resolution, can help reject a large fraction of pileup.

The rest of the effect must be modeled.



Sources of background



Simulation of RHESSI background components by T. Wunderer

Sources of background:

Cosmic diffuse photons: dominates unshielded or wide-aperture instruments below ~ 100 keV

Earth-atmospheric photons: dominates an unshielded, low-Earth orbit instrument above ~ 100 keV. Strong positron-annihilation line at 511 keV. Due to interactions of cosmic rays, therefore lowest near magnetic equator

Prompt cosmic-ray interactions in detectors: tend to leave > 10 MeV in large detectors, little confusion with solar photons

continued.......

Sources of background, continued:

Prompt cosmic-ray interactions in the spacecraft:
Similar spectrum to Earth-atmosphere component

Direct interaction and bremsstrahlung from particles:
Huge, temporary backgrounds possible from SEPs (outside magnetosphere) or radiation belts (inside). Only an equatorial LEO is completely safe.

Radioactivity: delayed result of nuclear interactions of cosmic rays; primary component is in the detector itself, but lines can also be seen from surrounding materials

Natural radioactivity: 40K, U, Th isotopes occuring naturally in the spacecraft. Generally minor. "Cleaner" materials (generally old) can be used.

Coping with background:

Scale of the problem:

a B-class microflare will dominate any background < 10 keV

an M-class flare will dominate any background < 30 keV

a large X-class line flare will dominate or at least compete with background at all energies

Coping with background: Reducing it

Passive shielding: blocks photons but can glow with cosmic-ray secondaries just like the atmosphere

Generally useful only below 100 keV, to block cosmic photons

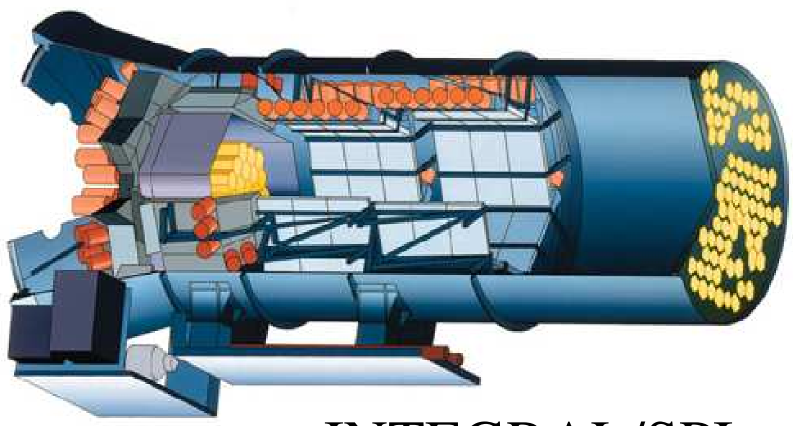
"Graded-Z" shielding: k-shell fluorescence from heavy shielding element is blocked by a slightly lighter element, and so on.... RHESSI uses Ta/Sn/Fe/Al

Coping with background: Reducing it

Active plastic scintillator shielding: tags incoming cosmic rays; electronic veto during time of their prompt influence. No effect on incoming gammas or delayed radioactivity.

Heavy active shielding (CsI, BGO, etc.): tags incoming cosmic rays **and** blocks photons, but can create intense local neutron environment, enhancing detector radioactivity.

Best geometry is a "well" -- fewest leaks possible:



INTEGRAL/SPI

Your shield probably weighs several times what your prime detectors do -- Can you use it for science? Is it your best investment of money and weight?

Coping with background: Reducing it

Choice of orbit: low-Earth equatorial is best, followed by orbit outside the magnetosphere. Exposure to the Earth's radiation belts is worst. The belts touch the atmosphere at the South Atlantic Anomaly.

SEPs give you a huge background when not protected by the magnetosphere. Can be a big problem for studying large flares since they tend to come in bunches

Keep field of view and detector volume as small as possible consistent with your science

Focus! This allows you to connect a small detector with a large collecting area. Excellent for faint astrophysical sources or nanoflares; could be deadly for large flares due to deadtime & pileup

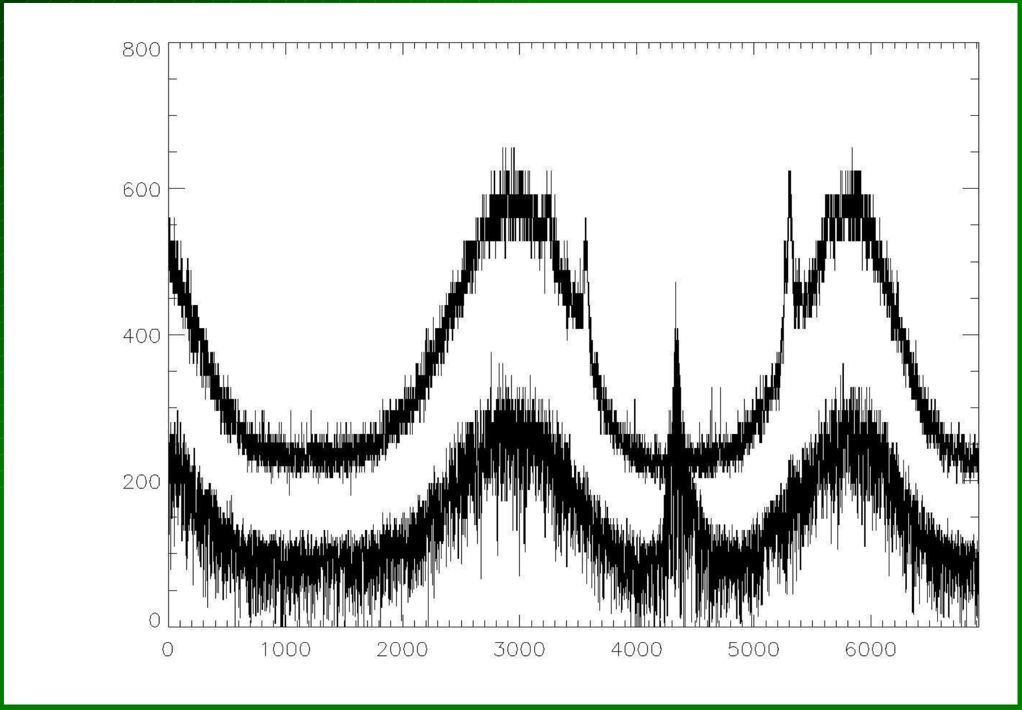
Coping with background: Subtracting it

Good background subtraction is necessary but not sufficient: if background is >> signal, Poisson fluctuations in background can dominate errors even if the background is 100% understood

When Poisson errors are small (many counts), background systematic errors become important unless background is negligible

In practice, time variability makes pure modeling difficult; subtract background taken at an "analogous" time

RHESSI lightcurves, 2 hours, showing bkg variation & flare



Efficiency and off-diagonal response

In the hard x-ray range, often only a correction of efficiency (effective area) versus energy is necessary:

(counts/s/keV seen at E) / (effective area at E in cm2) =
photons/cm2/s/keV incident

At high energies, many counts are often shifted to low energies instead of just lost, and this simple division becomes a matrix inversion instead.

At very low energies, window absorption can be important. This is normally just an efficiency correction.

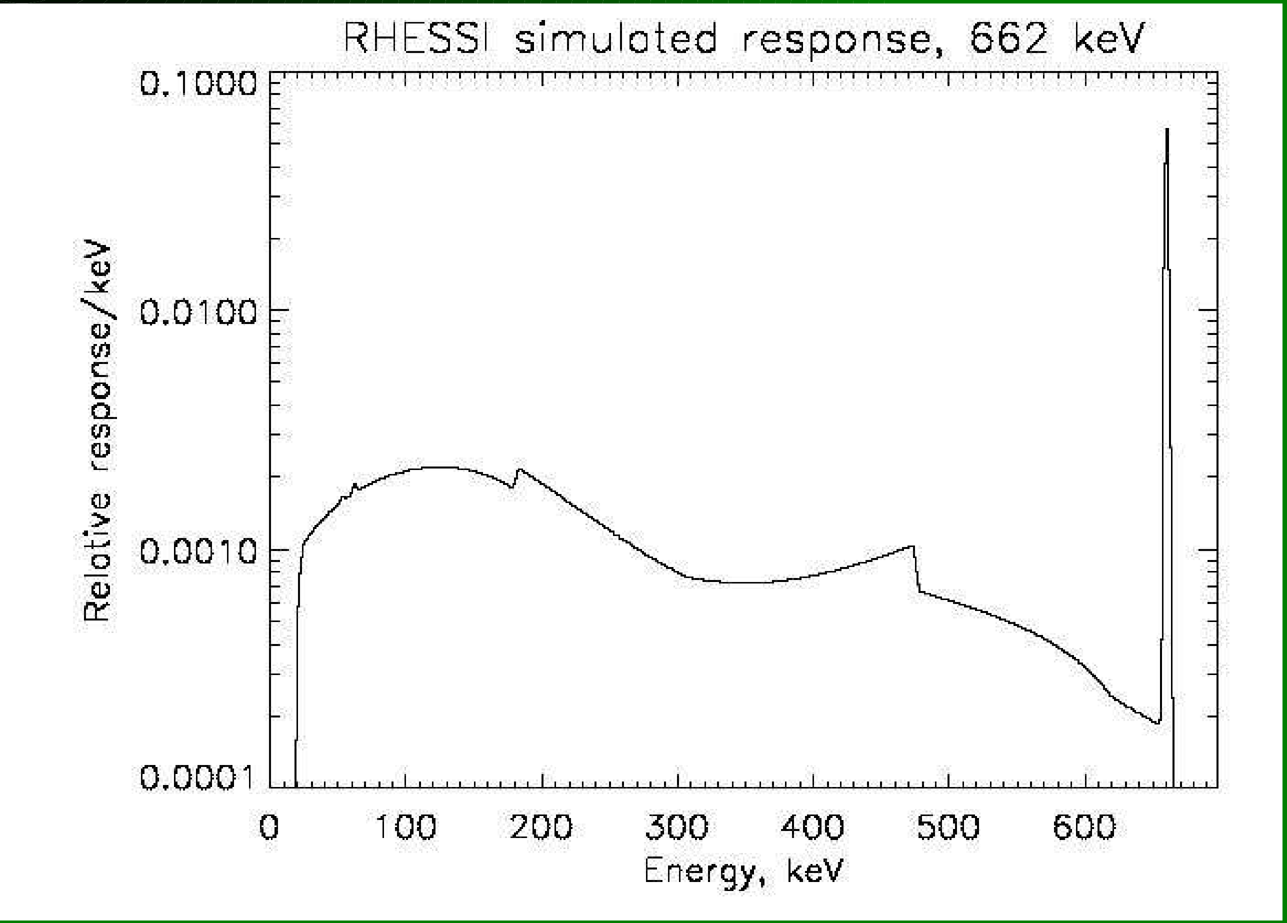
Subtlety: Fluorescence escape from the crystal (say 13 keV --> 4 keV) can dominate true 4 keV stuff if the latter is strongly absorbed.

Off-diagonal response:

Recorded energy differs from photon energy. Common reasons:

Compton scatter before entering detector
Compton scatter out of detector
Fluorescence outside
Fluorescence escape
511 keV escape
Annihilation outside

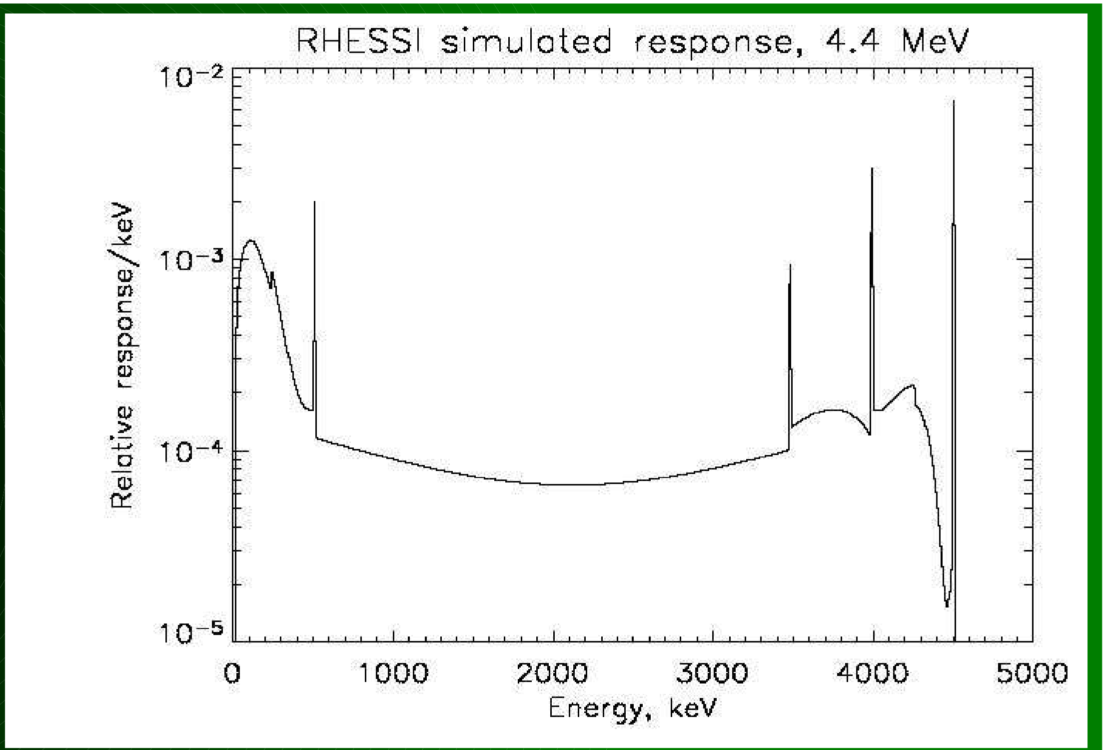
Energy resolution imperfect (always); only time count energy > photon energy

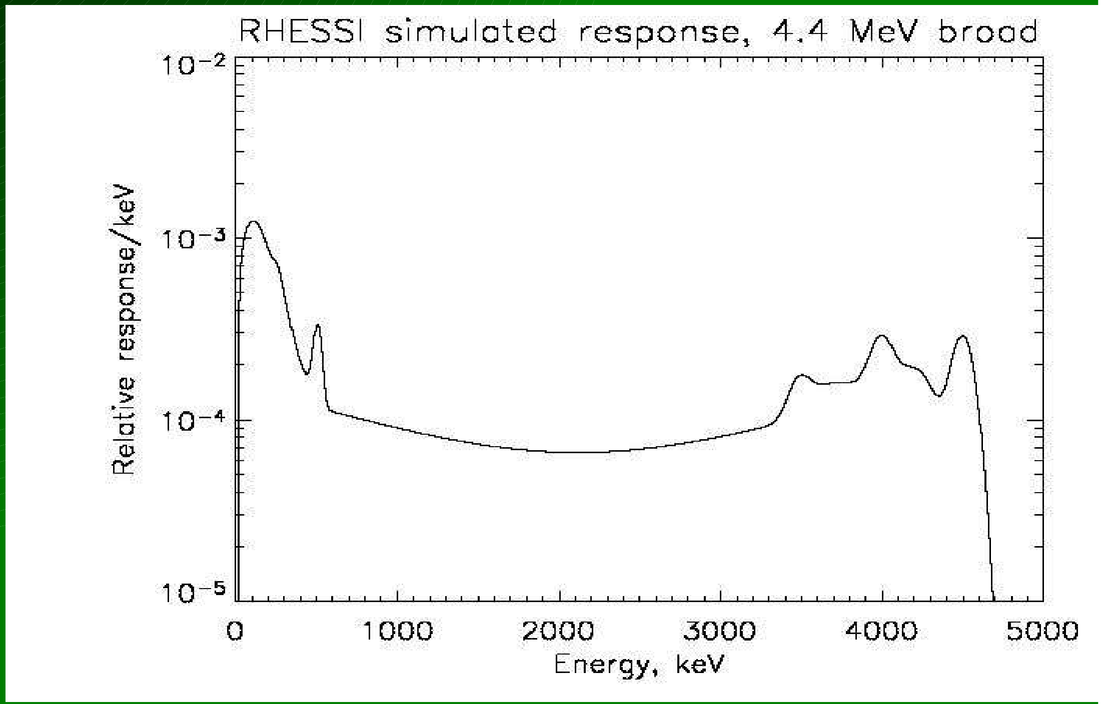


High energy resolution serves to make lines more identifiable; also reduces background for line identification.

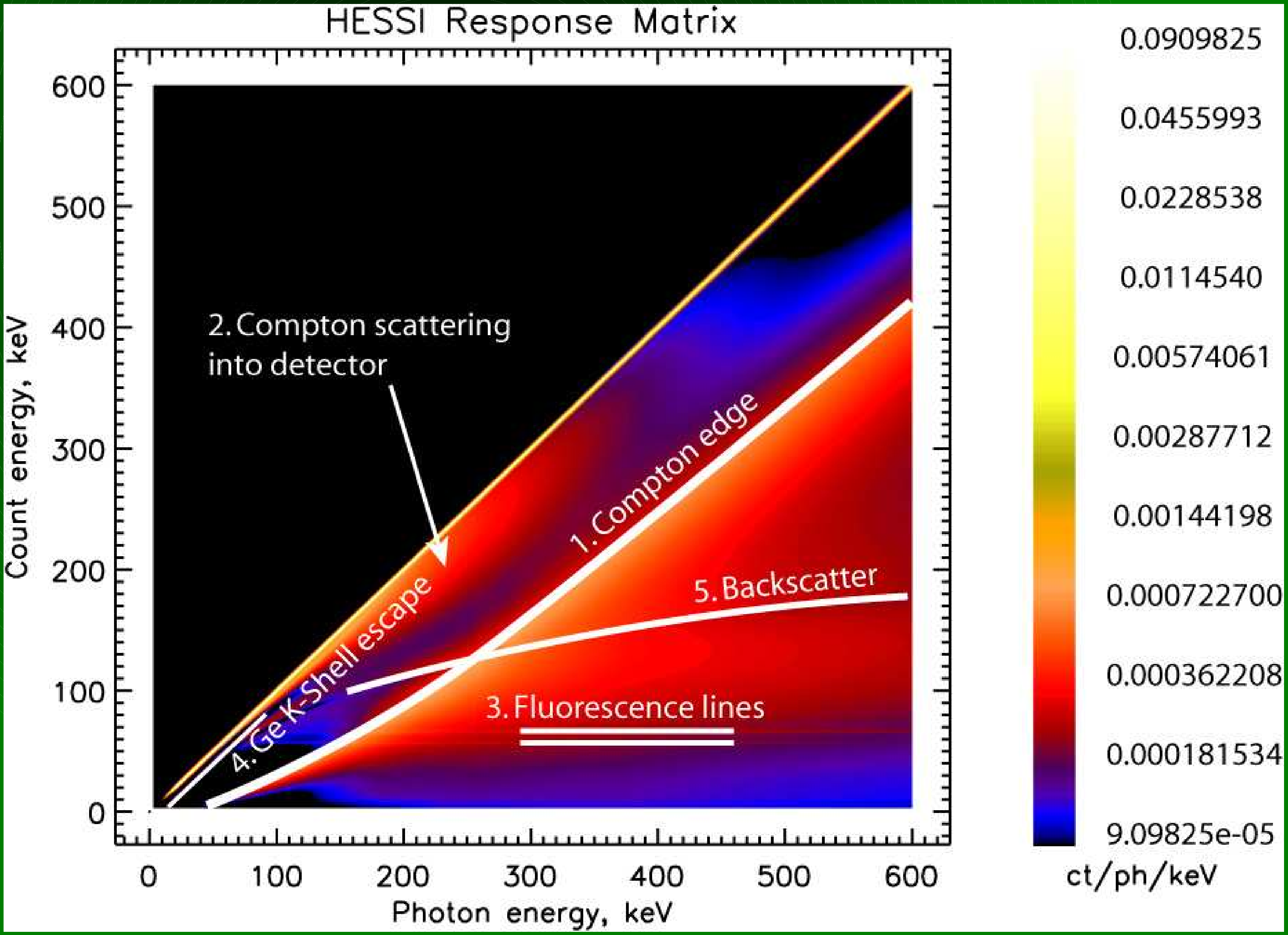
Naturally broad lines are more difficult to see even with a high resolution instrument.

Off-diagonal (Compton) response is reduced both by more efficient detectors (higher Z, larger) and by active shielding, which suppresses outward Comptons as well as inward background (e.g. SMM/GRS vs RHESSI).

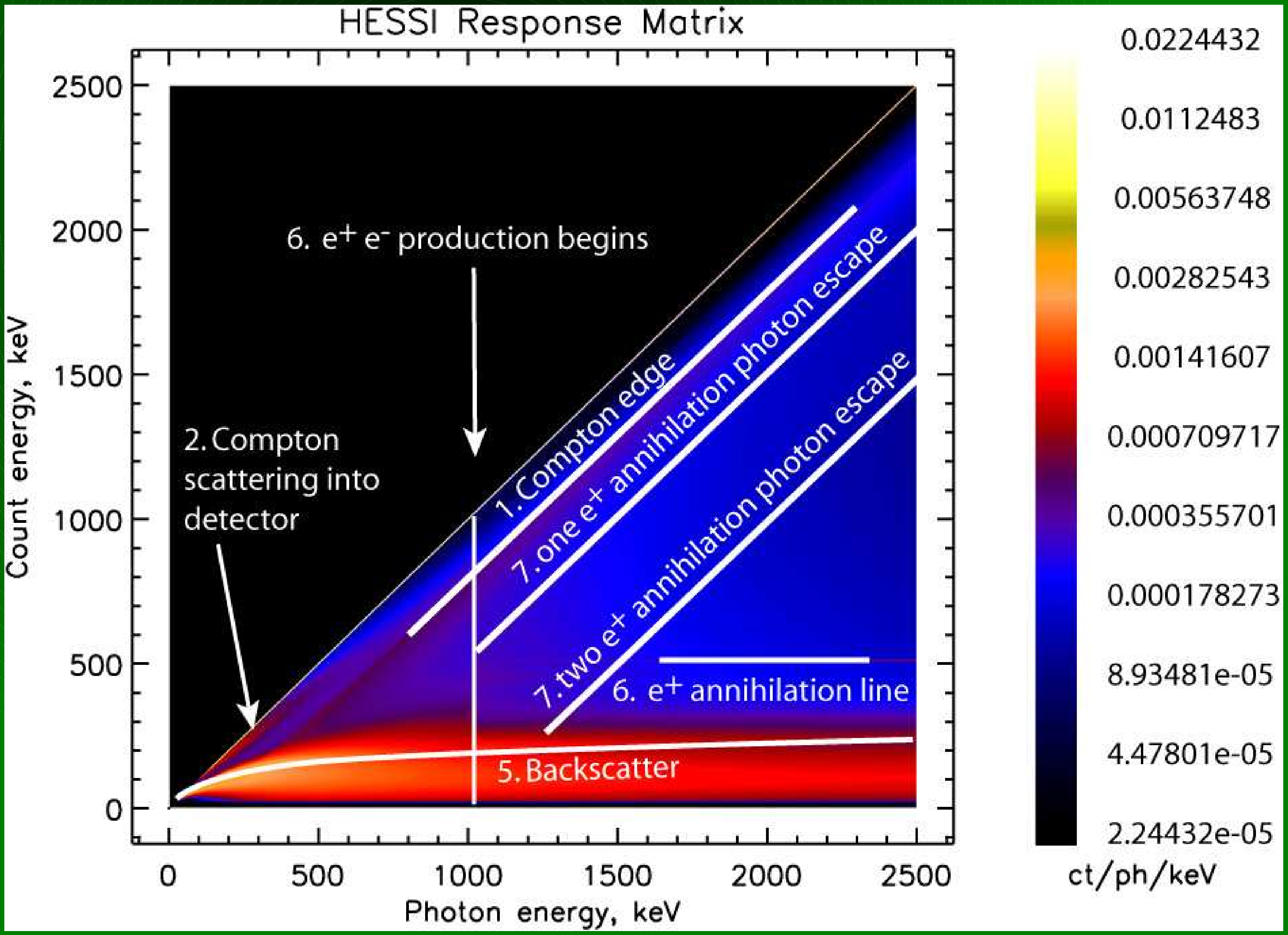




Response matrix at low energies, annotated by H. Hudson



Response matrix at high energies, annotated by H. Hudson



Order of operations is important !

Gain correction
Livetime & Pileup

These first: background spectra may not have same gain, livetime

Background Subtraction

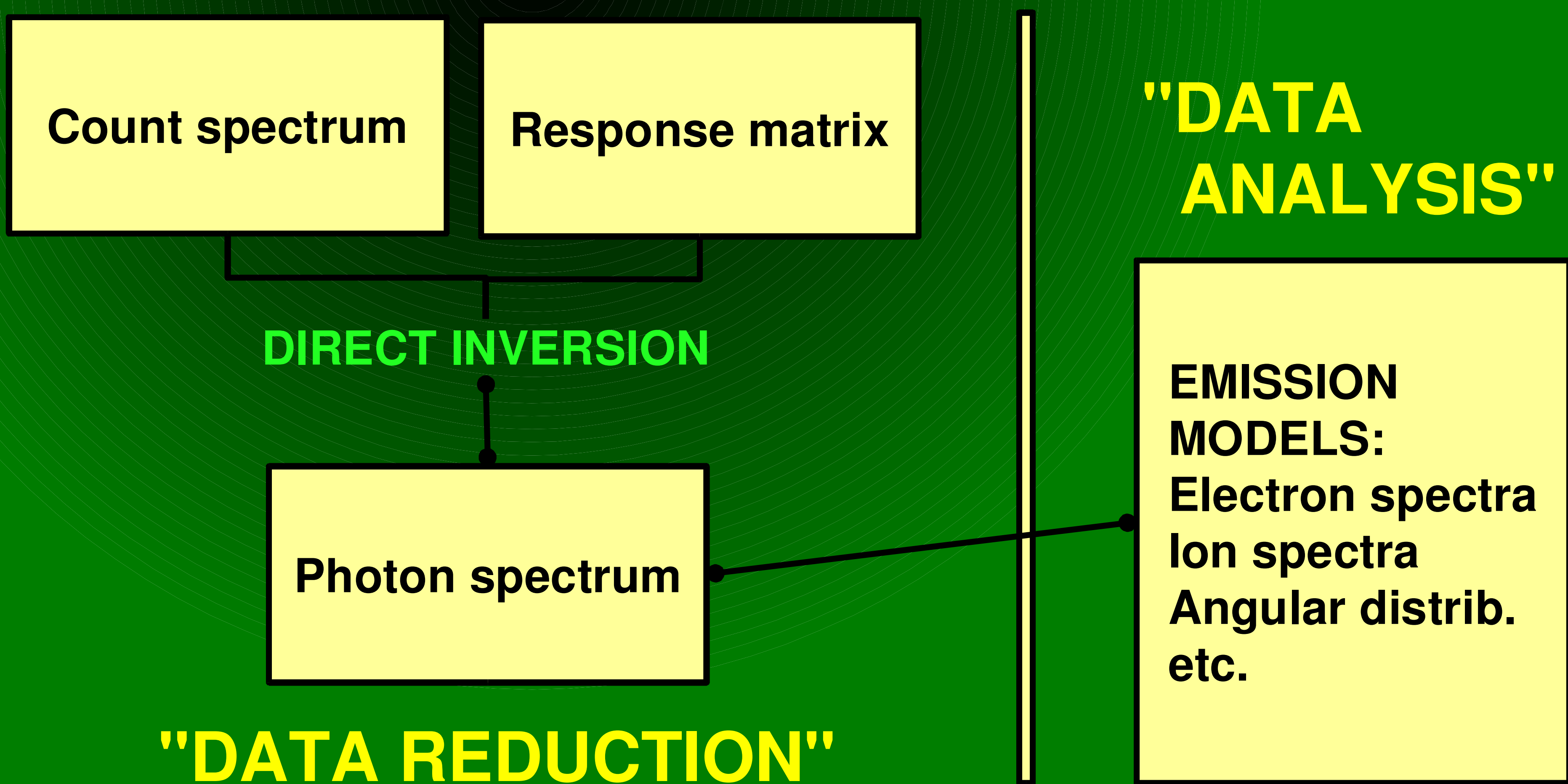
This next: background doesn't have same response characteristics

Response matrix Deconvolution

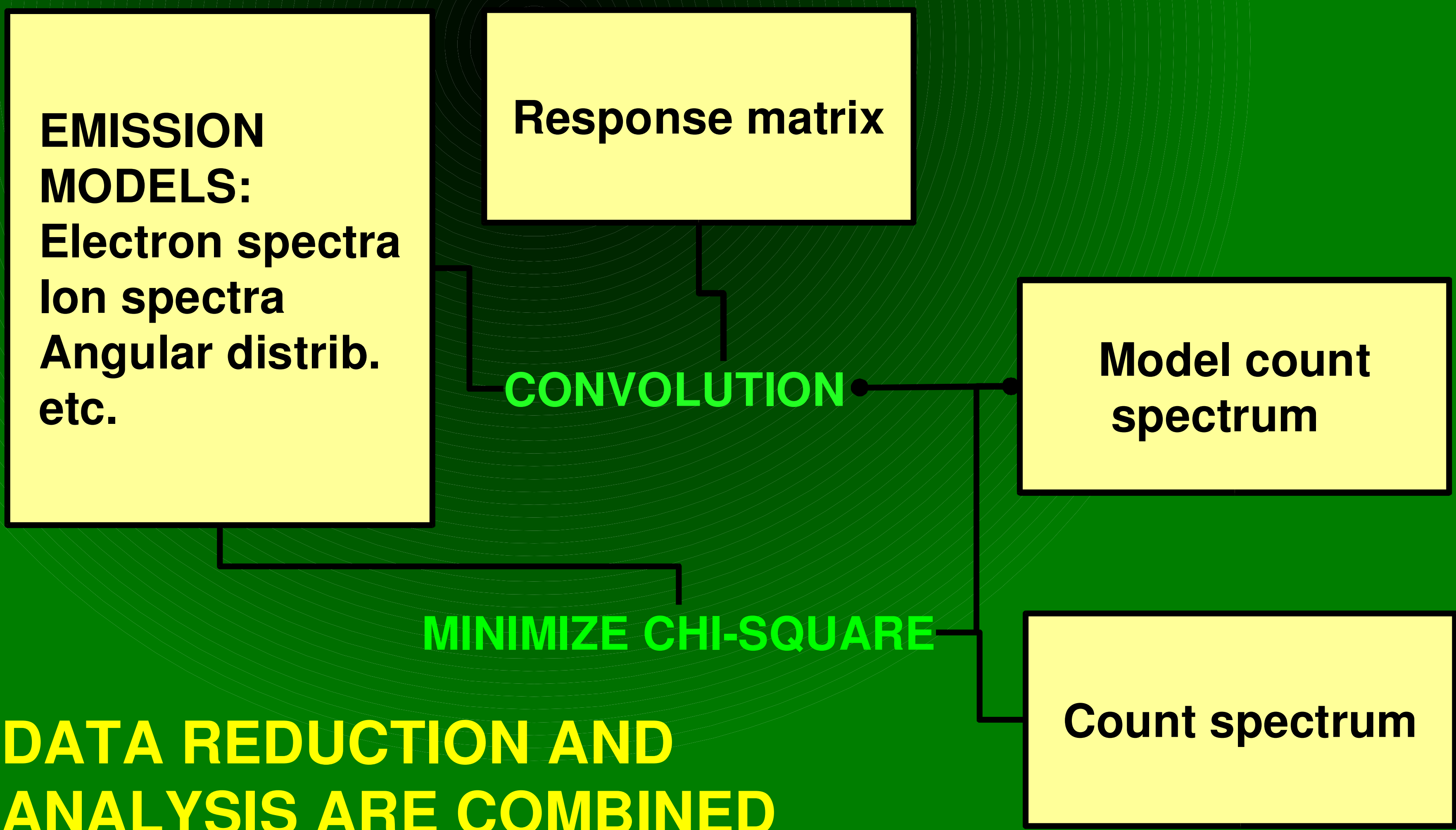
This is last and hardest; analogous to the inverse problem in imaging

Given gain/livetime/pileup/background corrected spectrum (count spectrum), two routes to an "instrument-free" photon spectrum:

THE DIRECT ROUTE:



THE DIRECT ROUTE is unfortunately very difficult; can only be done for simple spectra with excellent counting statistics (see work by Johns-Krull, Piana, Kontar, Brown). More usually, use **FORWARD FITTING:**



DATA REDUCTION AND ANALYSIS ARE COMBINED

Error propagation:

For gamma-ray energies, Poisson statistics are the dominant error. Limitations on using sqrt(N) for error:

> You must do this in units of **raw counts only**, not counts/s, not background subtracted counts
>
> It's inaccurate for N<10 or so. sqrt(N+1) is slightly better but still no good for N<3. Binning counts to broader energy channels to get N ~ 10 is favored by duffers but deplored by Bayesians.

Remember to include error on background too.

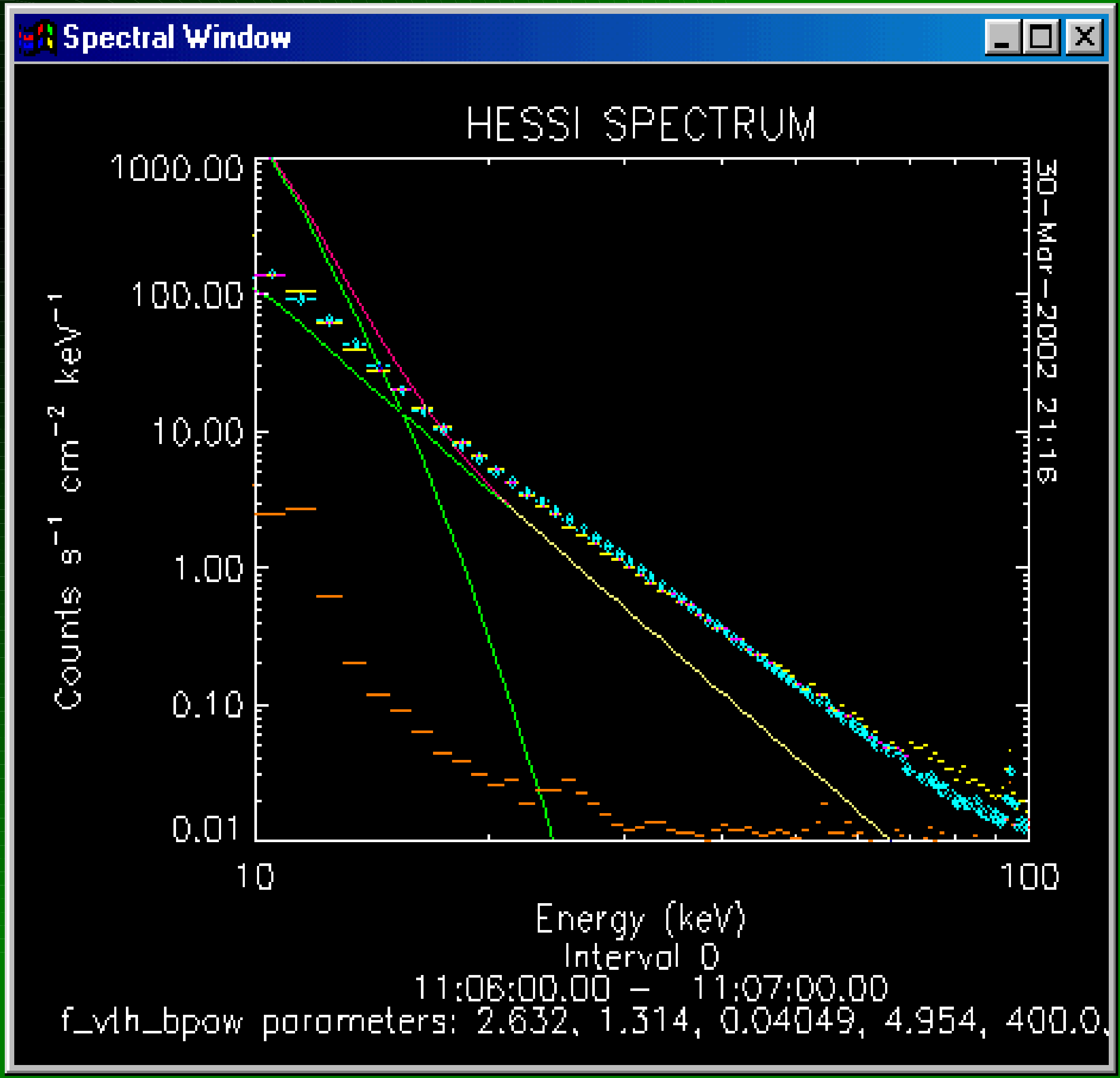
For x-rays, calibration uncertainties probably dominate.

Errors propagated as usual. Very nice compact book:

A Practical Guide to Data Analysis for Physical Science Students, L. Lyons

Example: RHESSI SPEX program (by R. Schwartz)

Image by B. Dennis from "RHESSI Spectroscopy First Steps"



Wheels not to reinvent:

- Instrument response, solar and atmospheric photon propagation: GEANT3, GEANT4
  - http://wwwinfo.cern.ch/asd/geant/
- Space radiation environment and doses: SPENVIS
  - http://www.spenvis.oma.be/
- Instrument background prediction: MGGPOD (includes GEANT)
  - http://sigma-2.cesr.fr/spi/MGGPOD/
- Cross-section lookup: NIST XCOM
  - http://www.physics.nist.gov/PhysRefData/Xcom/Text/XCOM.html
- Radioactivities, fluoresence, isotopes, etc.:
  - http://ie.lbl.gov/toi/